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# Shock-Recovery Experiments of Sandstone Under Dry and Water-Saturated Conditions

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Lawrence Livermore National Laboratory

**September 3, 1999**

# SHOCK-RECOVERY EXPERIMENTS OF SANDSTONE UNDER DRY AND WATER-SATURATED CONDITIONS

**Michael Hiltl[1], Robert P. Swift[2], Carl R. Hagelberg[2], Theodore C. Carney[2] and Wiliam J. Nellis[1]**

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**Abstract.** Shock-recovery experiments have been performed on Berea Sandstone under dry and water-saturated conditions using a single-stage light-gas gun. Stress levels in the range between 3.1 and 9.8 GPa were achieved by impacting projectiles in a recovery fixture. The microstructural damage of the shocked samples were analyzed with scanning electron microscopy (SEM), laser particle analysis and X-ray computed micro tomography (XCMT). The dry samples show strongly and irregularly fragmented quartz grains with an considerably reduced porosity. In contrast, the water-saturated specimens have less grain damage and higher porosity. The water in the pores distributes the stresses which reduce the contact force between the grains during the shock compression. The dynamic fragmentation of the grain-grain interactions was modeled by explicitly treating the grain-pore structure using the Smooth Particle Hydrodynamic (SPH) computational method. This is a continuum Lagrangian gridless approach that features particles.

## INTRODUCTION

Dynamic shock-wave experiments [1, 2] on geological materials have been carried out to understand the mechanical behavior associated with many important geologic phenomena, for example oil and gas recovery, mining, meteoritic impact, earthquakes and underground explosions. Our motivation for this work is to obtain a quantitative assessment of shock-induced grain damage and to provide damage data for correlation and comparison with explicit grain/pore scale numerical modeling, similar to that described in [3]. Furthermore, we want to increase our understanding of the phenomenology of heterogeneous grain-grain interactions under dynamic loading. The modeling of the shock-recovery experiments are reported in this volume [4]. Application for this study comes in part from the oil and gas recovery, where shaped-charge jets are used to perforate the wellbore casing to provide connectivity to the surrounding reservoir rock. The jet creates a localized crushed zone [5, 6] surrounding the tunnel which hinders recovery of hydrocarbons. In this study we examine grain fragmentation caused by short duration stress waves, similar to perforation loading, of Berea sandstone (Table 1), one of the most commonly used rock standards in petrophysical studies [7].

**TABLE 1:** Properties of Berea Sandstone.

| | |
|---|---|
| Porosity: | 21.92% |
| Bulk density: | 2.077 g/cm$^3$ |
| Grain density: | 2.631g/cm$^3$ |
| Average grain size: | 0.15 mm |
| Modal analysis [8]: | 75% quartz, 10% clay, 10% feldspar, 5% calcite |

## EXPERIMENTAL SETUP

Shock-recovery experiments for dry and water-saturated conditions have been performed by using a light-gas gun with a bore diameter of 35 mm.

| Shot Nr. | Target Dimensions [mm] | Impactor Material | Impactor Thickness [mm] | Impact Velocity [km/s] | Impact Pressure [GPa] | Pressure Sandstone* [GPa] | Condition |
|---|---|---|---|---|---|---|---|
| 565 | 22.4 X 5.0 | Al | 2.97 | 0.76 | 6.1 | 3.6 | Dry |
| 575 | 22.5 X 4.6 | Al | 3.03 | 0.89 | 7.2 | 4.3 | Dry |
| 576 | 22.5 X 4.6 | Cu | 3.02 | 0.84 | 9.8 | 5.8 | Dry |
| 605 | 22.4 X 5.0 | Al | 3.03 | 0.78 | 6.3 | 3.7 | Dry |
| 606 | 22.4 X 14.8 | Al | 6.25 | 0.76 | 6.1 | 3.6 | Dry |
| 607 | 22.4 X 14.9 | Al | 3.02 | 0.39 | 3.1 | 1.6 | Dry |
| 608 | 22.4 X 14.6 | Al | 3.02 | 0.80 | 6.4 | 3.7 | Dry |
| 609 | 22.4 X 14.7 | Cu | 2.98 | 0.85 | 9.8 | 5.8 | Dry |
| 610 | 22.4 X 5.0 | Cu | 2.98 | 0.83 | 9.7 | 7.7 | Wet |
| 611 | 22.4 X 14.5 | Al | 6.21 | 0.76 | 6.1 | 4.9 | Wet |
| 613 | 22.4 X 14.7 | Al | 3.02 | 0.39 | 3.1 | 2.5 | Wet |
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**TABLE 2:** Experimental datas for the shock-recovery experiments on Berea sandstone. *Finite element computer calculations.

All sandstone samples were confined in an aluminum capsule surrounded by a recovery-fixture of the same material. Figure 1 shows the target setup for the experiments under dry conditions.

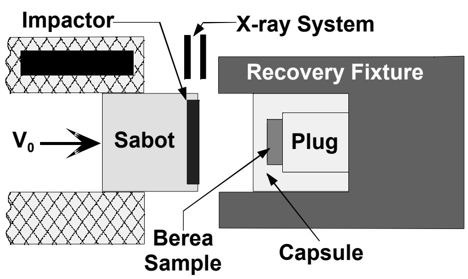


**FIGURE 1:** Experimental situation short before the impact.

The desired stress levels between 3.1 and 9.8 GPa at the front part of the capsule were achieved by impacting the sample with an aluminum 1100 or an OFE copper flyer plate. Flyer thicknesses of 3 mm and 6.25 mm were used to provide pulse durations of approximately 1μs and 2μs, respectively. Table 2 list the experiments we conducted.

## EXPERIMENTAL RESULTS

The shock-recovered samples were cut in two halves. One half was analyzed using a Tracor Northern SEM. Laser particle size analysis using Microtrac-X100 was performed on the other sample half. XCMT images were obtained on two samples at the National Synchrotron Light Source at Brookhaven National Laboratory. In this paper we focus on the damage behavior of the quartz minerals. We did not look for high-pressure phases of quartz [2].

### Scanning electron microscopy

Backscattered SEM images were taken along the center line from the impact side to the opposite capsule backside. In the undamaged sandstone, shown in Figure 2, the shape of the grains and pores are irregular. The majority of the pores are interconnected. In some grains, pre-existing cracks can also be observed.

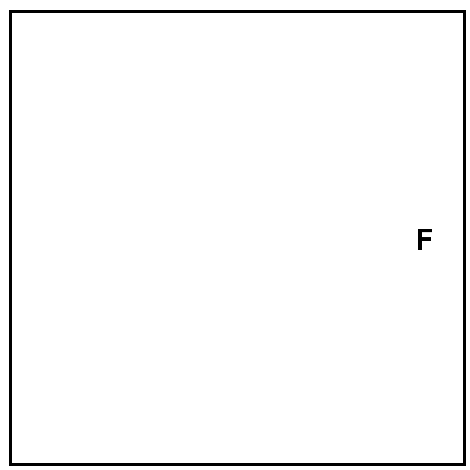


**Figure 2:** Undamaged Berea Sandstone (Q=Quartz, F=Feldspar, C=Clay, P=Pore).

Near the impact side of the dry sample impaced at 3.1 GPa, all quartz-grains are irregularly fractured and fragmented (Fig. 3).

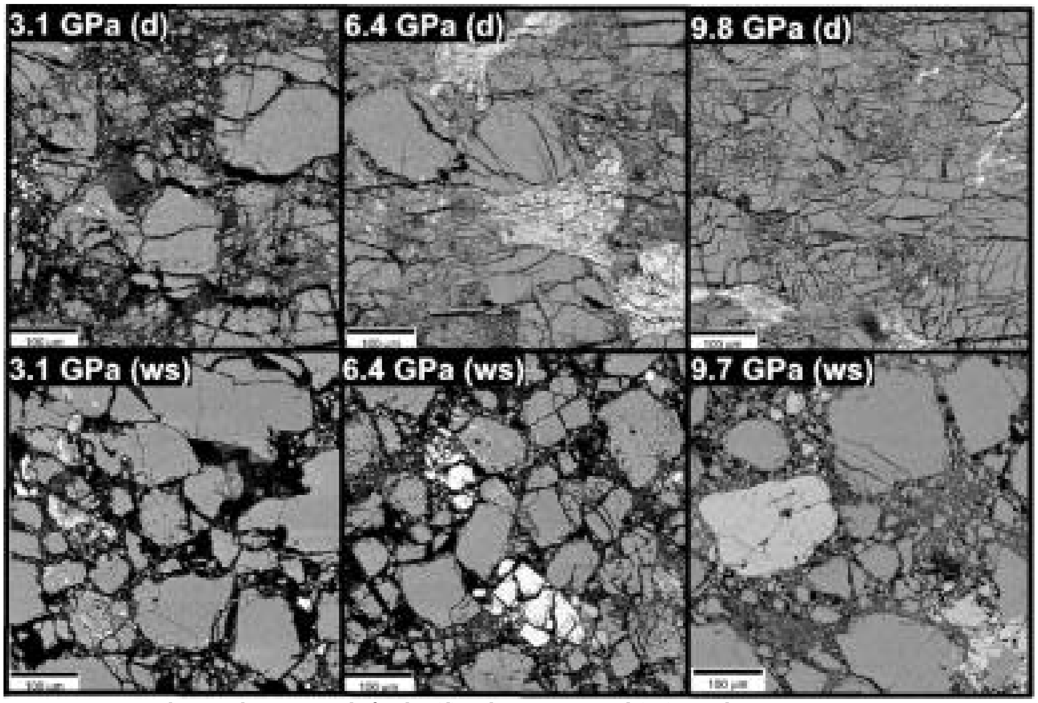


**FIGURE 3:** SEM micrographs near the impact side for dry (d) and water-saturated (ws) samples.

This is caused by grains being driven into each other as the shock front propagates through the sample. Overall, this sample has still an observable remnant porosity. As a result of stress attentuation from the front to the back of the sample, a decrease in damage is observed in the 15 mm thick sample. Much less fragmentation occurred near the backside of the sample. In contrast, the grains in the dry samples shocked at 6.1 GPa (Fig. 3) showed extreme fragmentation and fractures near the impact side. All the pores in this region were closed. The rear of these samples still had observable porosity with less damaged grains. The grains near the impact side in the dry sample loaded to 9.8 GPa (Fig.3) were completely fragmented with no observable porosity remaining. But near the rear of the sample, there were still pores visible and significantly less grain damage.

Compared to the dry samples, the grain damage in the water-saturated specimen was far lower and the reduction of the porosity was significantly less. This was a result of the pore fluid distributes the interactions between grains. Also, the difference in the grain damage between impact side and backside of the sample is not as great as observed in the dry samples. Samples shocked with the longer duration pulse showed more grain damage and pore compaction than those shocked with the shorter pulse.

### Laser particle analysis

Particle size distributions were determined by an angular light scattering technique. For each sample a total of three measurements were done and the average grain size was calculated. The measurements show a clear reduction of the average grain size in all shocked samples compared to the undamaged material. Figure 4 illustrates the difference in grain size between dry and wet samples impacted to about 6.1 GPa, as well as the difference between the regions near the impact side, mid, and the backside of the samples. Some samples showed a smaller grain size in the middle region of the sample than in the impact region. We presume that this is caused by rarefraction waves which converge in the mid region from the edges of the capsule containing the sandstone. Computer simulations support this speculation.

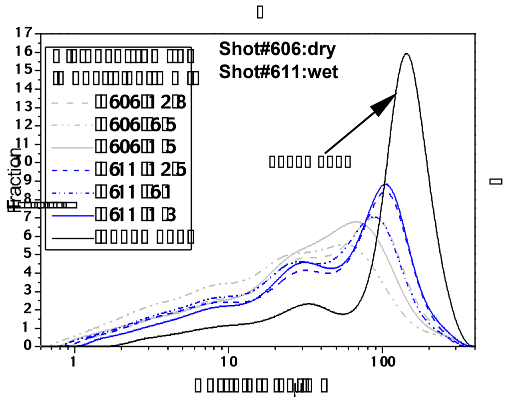


**FIGURE 4:** Differences in the results of laser particle analysis for samples 606 (dry) and 611(wet) compared to the undamaged material.

### X-ray computed micro tomography

Small cores (2 mm) were taken from the samples parallel to the axis of impact. The XCMT process creates a stack of images each of which lies in plane prependicular to the cylinder axis. Figure 5a shows a undamaged sample and provides an idea of the resolution obtained using XCMT. Figure 5b illustrates a XMCT slice of samples 608 roughly 94 μm from the impact side. Qualitatively, there are a few large grains and many small grains near the impact surface. Further away from the impact surface there are comparatively more large grains left intact.

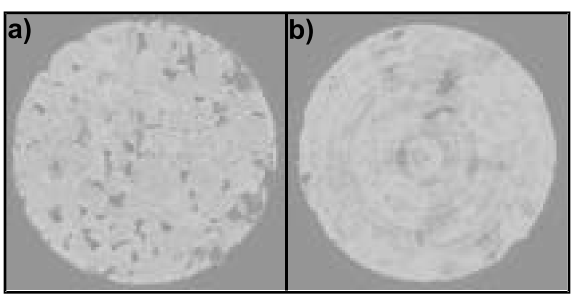


**FIGURE 5:** XCMT-micrograph of a) undamaged sandstone and b) experiment 608.

The XCMT data has not proven to be quantitatively useful at present due to its relatively coarse resolution (3.6 μm per pixel). At this point the data are useful for a qualitative comparison and support SEM observations. The XCMT data might prove useful for additional information regarding damage mechanism when further analysis techniques are developed, for example quantitative statistical image analysis in two and three dimensions.

## CONCLUSIONS

Shock-recovery experiments on dry and water-saturated Berea Sandstone have been performed in the rage between 3.1 and 9.8 GPa using a single-stage light-gas gun. Specific conclusions are: 1) increasing grain damage in dry and water-saturated samples with increasing stress-levels; 2) reduced porosity with increasing shock-pressure; 3) significant differences in grain damage and porosity between dry and water-saturated samples; 4) decreasing grain damage and increasing porosity with increasing distance from the impact side in the 15 mm thick samples; 5) damage increases with shock-pulse duration.

## ACKNOWLEDGMENT


This work was performed at Lawrence Livermore National Laboratory under the auspices of the U.S. Department of Energy under contract No. W-7405-Eng-48.


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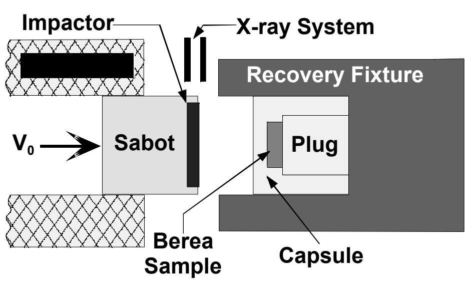


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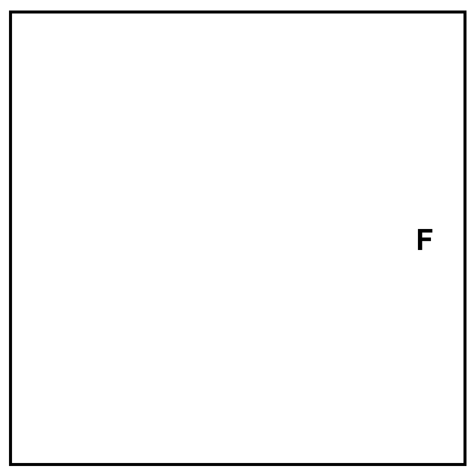


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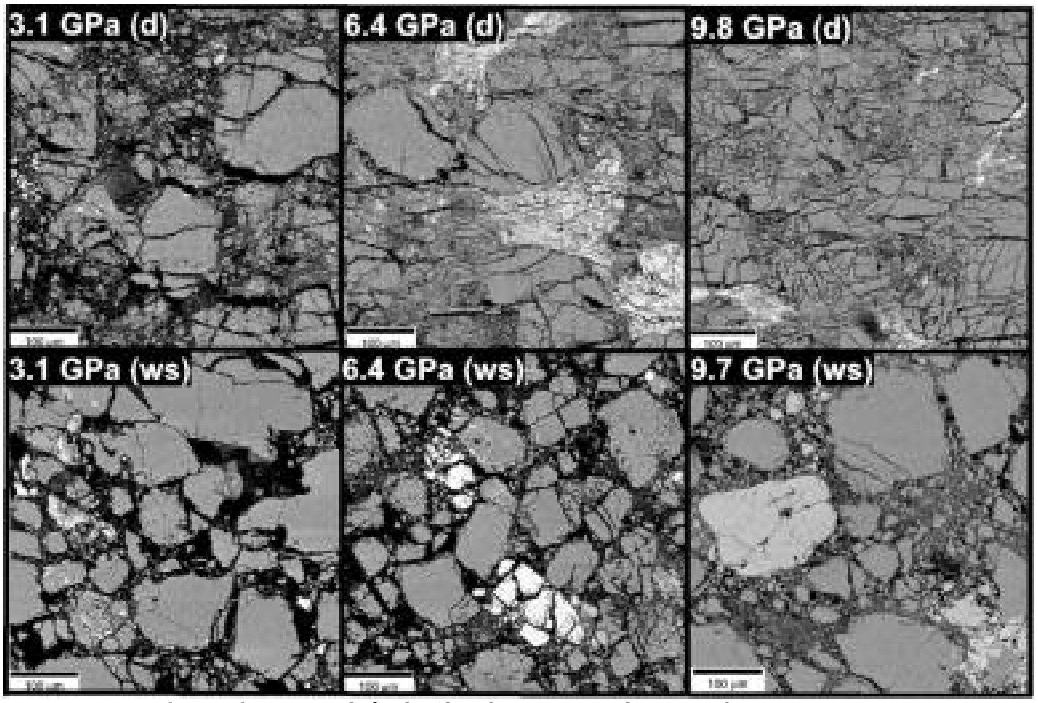

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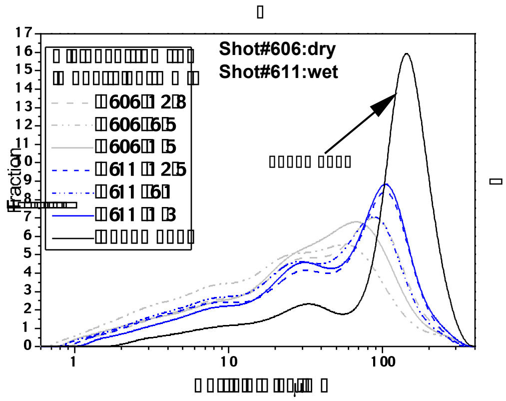


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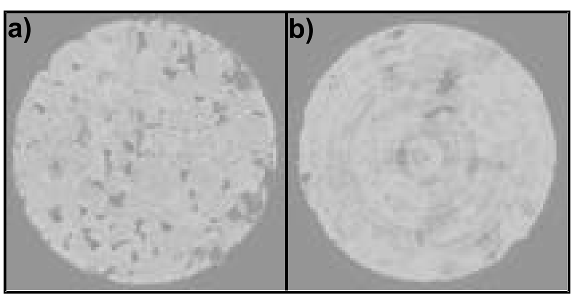


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